UDC 534.846.6

BBC

RESEARCH DEPARTMENT

1969
THE QUEEN'S AWARD
TO INDUSTRY

REPORT

[redacted]

Acoustic scaling:
General outline

No. 1970/13

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

RESEARCH DEPARTMENT

ACOUSTIC SCALING: GENERAL OUTLINE

Research Department Report No.1970/13
UDC 534.846.6

It uses SI units in accordance with B.S. document PD 5686.

H.D. Harwood, B.Sc.
A.N. Burd, B.Sc., F.Inst.P.

D. Maurice

Head of Research Department

(PH-59)

Research Department Report No. **1970/13**

ACOUSTIC SCALING: GENERAL OUTLINE

(PH-59)

ACOUSTIC SCALING: GENERAL OUTLINE

SUMMARY

An account is given of the possibilities of forecasting the acoustic properties of studios and concert halls by means of small-scale acoustic models. It is shown that the factors involved scale directly with the exception of air absorption and that even this can be made to scale closely if an appropriate degree of humidity is employed.

Some of the problems of instrumentation are discussed and possible solutions are suggested.

1. INTRODUCTION

Within the next ten years it is expected that several new music studios will be constructed, either as new buildings or as modifications to existing ones. A considerable amount of acoustic design work will therefore be necessary; it would not be practicable to copy existing designs as the architects' use of differing modern materials and building methods will affect the acoustic properties of the studios. This means that each new music studio will present a fresh challenge to the ingenuity of the acoustic engineers to obtain the optimum result as economically as possible.

Faults in the basic design which affect the acoustics of a building are not normally capable of correction after construction has started and even if some modification is possible it is likely to prove expensive. Errors in acoustic treatment can usually be corrected after nominal completion but, once again, the expense involved is considerable and any steps which can be taken to prevent such errors are therefore worth considering in view of the savings* which might result.

It would be extremely useful to an architect to be able to determine the acoustical effect of various changes in design if this could be done easily and without too great a cost. For example, the influence on sound quality of a reflector over the orchestra could be examined subjectively in different parts of the hall.

A technique which potentially permits the objective and subjective evaluation of the acoustic quality of an auditorium to be made in advance of its construction is that of acoustic modelling. This technique was first proposed for auditorium design using simple optical techniques. In 1926 both Schlieren spark methods[1] and ripple-tank methods[2] were employed at the National Physical Laboratory (N.P.L.). Spandöck[3] in 1934 worked out the basic physics underlying the technique of acoustic modelling and objective measurements (of reflections, reverberation times, diffusion, etc.) were started at the Technical University of Munich as high-frequency transducers became available.

* The cost of the technical areas (not including offices, public rooms, etc.) of a typical new studio block is of the order of £750,000.

Within the last five years, however, acoustic modelling has received a new impetus in the work of Jordan[4] and Spandöck[5] who used transducers whose characteristics were good enough to provide stereo recordings from which a meaningful subjective judgement of acoustic quality could be made.

In 1968 it was decided that work to extend that carried out by Jordan and Spandöck should be carried out and this report is one of a series describing it.

2. BASIC PRINCIPLES

In a non-dispersive* medium such as air, the wavelength of sound is inversely proportional to the frequency. Thus if a model of a studio is made with a scale factor of 1/k the following conditions relative to those of the full-size studio, will be obtained or be required:

(i) The time between reflections will be reduced in the ratio 1/k, since the transmission medium in the model is air and the velocity of sound remains unchanged.

(ii) For similarity in wave-acoustic behaviour the sound wavelength must be reduced in the ratio 1/k. Therefore the frequencies must be increased in the ratio k/1.

(iii) The air absorption should have a value k times that applying at normal frequencies, since the path lengths are reduced by this ratio.

(iv) If the acoustic impedances of the surfaces of the model over the increased frequency range are made equal to the impedances of the corresponding surfaces in the full-size studio, over the normal frequency range, it follows that, for a constant mean absorption coefficient, the reverberation time will be reduced in the ratio 1/k.

Thus the model is constructed to the desired scale so that the absorption of the surfaces and of the atmosphere correspond to those of the full-size environment. A stereo tape recording of the required programme material is made

* in this context

in free field, i.e. 'dead', surroundings and is reproduced in the model through suitable high-frequency transducers at a tape speed k times that used for the original recording. The output from the microphones in the model is recorded at the high tape speed and subsequently reproduced at normal speed for subjective assessment. In this way the acoustics of the model should correspond to those of the full-size studio and can be judged accordingly.

Similarly the variation in reverberation time with frequency and the impulse response can be measured objectively in the model to enable the optimum values[6] to be determined for the particular use to which the studio will be put.

3. THE MODEL

3.1. Model Construction

The basic structure of a building suitable for studio use is usually massive in order to provide adequate acoustic protection from external noise and to prevent sounds from the studio affecting other areas. Within the frequency range where such a structure behaves as a mass (the mass-law region) a model should have walls whose thickness is 1/k of the full-size value; the same transmission loss will then be found at k times the normal frequency. The upper frequency limit at which mass-law behaviour breaks down, known as the critical frequency,* is the coincidence frequency for bending waves at grazing incidence, while the lower frequency limit is that just below the fundamental flexural mode, i.e. for a stiffness-controlled condition. Both these frequencies are dimensionally inversely proportional to length and therefore scale correctly when all dimensions are reduced. If it is not intended to use the model for studying insulation, its construction may be simplified by using alternate materials such as timber, rather than scaled skins of brick, concrete or other materials.

Absorption which arises from vibration of the structure is normally small compared to that which is added as acoustic treatment. There are occasions however when this is not true and an example may be seen in Maida Vale Studio 1 where excess absorption at low frequencies is attributed to vibration of the ceiling. As was stated above, the resonance frequency of a scale structure should be correctly increased by the scale factor k but in some cases special measures may have to be taken to see that the damping of the structure is also correctly scaled.

In this connection the time for vibrations in a structure to decay to 1/1000 of their original amplitude (60 dB decay) is given by:[7]

$$T = \frac{2 \cdot 20}{\eta f_0}$$

where η is the decay factor

f_0 is the resonance frequency

* The frequency at which the wavelength of a sound wave in air is the same as that of a flexural vibration in the partition.

For a homogeneous metal plate η has been found to be approximately inversely proportional to frequency. For many materials with added damping the decay factor is approximately independent of frequency while for other materials an increase of decay factor with frequency has been found. Only materials whose decay factor is approximately independent of frequency scale correctly; an increase of the resonance frequency by k times causes a corresponding fall in decay time. Very little information is available in the literature on the variation of decay factor with frequency for practical materials.

Concert halls, opera houses and the like, with which the great majority of model experiments completed to date have been associated, rely on absorption by the audience to provide all but the low-frequency sound absorption. A music studio, which has a much smaller audience, if any, requires much more added absorption on the surfaces, and experiments are necessary to provide adequate modelling of the various types of acoustic treatment employed. In BBC studios this treatment is constructed in 1·2 m x 0·6 m modular absorbers with different types of treatment interspersed to provide some measure of diffusion. Pilot experiments are needed to model absorbers of this size and require the construction of a model reverberation room to test them.

The construction of the resonant absorbers for the model requires the experimental selection of special materials because mechanical damping in the materials used in full-size absorbers does not, in general, scale correctly. The problem is, however, eased by the fact that it is customary to adjust the damping of resonant absorbers experimentally by adding porous material behind the vibrating panel.

If the joints between different parts of the model are adequately sealed the sound insulation of the model at scaled frequencies should be comparable with that of a single studio wall at normal frequencies. Additional protection from outside noise is required such as might be provided for the full-size studio by the surrounding technical areas. However, the complication of ensuring complete sealing may not be so necessary if additional attenuation can be introduced for reflections from the walls of the room occupied by the model. In practice a room already treated with acoustic absorbers on the walls and ceiling is suitable and this ensures that, in conjunction with the energy loss involved in traversing the walls twice (once in each direction), a 50 dB ratio of signal to spurious reflection can be obtained.

3.2. Air Absorption

Sound-propagation measurements in air at high frequencies have shown an attenuation greater than the classical value, which took into consideration energy dissipation due to shear viscosity and thermal conductivity. The extra attenuation has been shown to be largely due to molecular relaxation absorption in oxygen with a relaxation time which is a function of humidity.

Classical attenuation increases as the square of the frequency and therefore scaling by a factor of k increases

the air absorption in the model by a factor of k which is the value required. The excess absorption may be minimised by reducing the percentage molar concentration of water vapour; this reduces the relaxation frequency and so reduces that portion of the total attenuation due to oxygen. Various experimenters have reported obtaining 3% relative humidity by drying the air on repeated circulation through a large quantity of silica gel. Preliminary experiments with a model reverberation-room however, have shown that silica gel is not a very efficient drying agent at very low humidities and that a synthetic zeolite is much more efficient for this purpose; relative humidities of about ½% have been obtained using it. Early measurements were found to be unreliable as the ordinary commercial hygrometers used were not suitable for these low humidities but a capacitive type has been acquired and has given consistent results. Occasional measurements made using wet and dry-bulb thermometers have confirmed its reliability.

To dry the air in a model studio a drying tank 90 cm x 70 cm x 75 cm has been designed using zeolite (about 75 kg) together with an 18 cm fan; heating elements are provided to dry the zeolite when not in use. With such equipment the air in a typical model studio is changed every 5 minutes and when the model itself is dry the air can be reduced to 4% relative humidity in 15 minutes.

The model itself is enclosed in a polythene tent with an air-trap door, so that adjustments can be made without greatly disturbing the humidity inside the model. To help in this regard the air inside the tent is kept at a fairly low humidity, about 30%, by a refrigerating dehumidifier.

4. MICROPHONES

The requirements for microphones fall into two classes; those for objective measurements and those for subjective assessments, the main difference being in the signal-to-noise ratio necessary. With pulse tests and reverberation time measurements, the ratio required is not high as it is possible to use narrow-band filters; also the uniformity of the frequency response is not as important as it is with subjective assessments. For subjective tests a weighted* signal-to-noise ratio of at least 50 dB is required if the assessment of sound quality is not to be affected by the noise, and a low equivalent noise level is therefore essential.

Spandöck used electrostatic microphones of the Sell type in which an insulated diaphragm is in contact with a roughened back plate. The axial frequency characteristics extended up to about 120 kHz but the size of the diaphragm, although not stated, appears from the photographs in his paper to be large and therefore the microphones would be highly directional at the upper end of the frequency band.

The only commercially-available microphone with such an extended frequency range is 6 mm in diameter; the axial frequency response extends to just over 100 kHz. It is a pressure-sensitive device and is therefore omnidirectional at the lower frequencies but at 100 kHz, where the wavelength is only 3 mm, it is rather directional. As supplied by the manufacturer, the noise level of this microphone is excessive for subjective work, but experiments show that a f.e.t. (field-effect transistor) head-amplifier can be made with a relative noise level some 15 dB lower than that of the amplifier supplied. There is also the possibility that the use of a radio-frequency biassing circuit[8] could further lower the noise level by several dB below that of the f.e.t. amplifier. The r.f. technique could not be applied to the Sell type of capsule as the electrical stability is not adequate.

Some experimental microphones, only 3 mm in diameter, have been developed but they are appreciably less sensitive than the 6 mm type and are thus unusable for the present purpose as the signal-to-noise ratio is too low.

As it is desirable to obtain stereophonic information about the acoustics of the model it will be necessary to use the spaced microphone technique (since the microphones are omnidirectional at the low and middle frequencies); the transducers could be set about 50 cm apart.

5. LOUDSPEAKERS

The requirements for the loudspeakers are twofold. Firstly a sufficiently high level of sound must be produced in the model to provide, in conjunction with the microphones, an adequate signal-to-noise ratio and, secondly, they should have appropriate directional properties over the whole frequency range. Taking the latter requirement first, various directivities, such as that of the human voice,[9] have been suggested by workers in the field. Other ideas include an omnidirectional source or even an extended source roughly simulating an orchestra; most of the musical instruments have a restricted frequency range and it would not be practicable to employ all the channels necessary to imitate an orchestra. The simplest approach is to use a pair of loudspeaker assemblies (radiating through 2π radians) covering the whole frequency range and to reproduce a stereophonic recording through them. This has the virtue that a stereo recording of non-reverberant music[10] can be replayed through two monitoring loudspeakers in the real studio and re-recorded for comparison with the corresponding recording made through the model. For pulse work and reverberation measurements such loudspeakers are also more convenient to use than an extended source. A 110 mm unit, having a plastic cone, has been developed for use as a low-frequency unit operating from 400 Hz up to 15 kHz and a number of electrostatic units, 25 mm in diameter, have been obtained to cover the frequency range 15 kHz to 100 kHz. These units may be combined to form loudspeakers for use in the model.

6. TAPE RECORDERS

It is necessary to record test material at a convenient tape speed, reproduce it at k times this speed, re-record

* CCIF 1949 'Measurement of noise in music circuits.' Specifies the weighting to be employed in measuring low-level noise in music circuits.

Fig. 1 - View of model studio showing model loudspeaker

the output from the model at this same high speed and, finally, reproduce it at the original speed for assessment or measurement.

The only type of instrument readily available which will cover the requirement is an instrumentation-type recorder. Unfortunately such machines are characterised by a signal-to-noise ratio which is not as high as that of professional programme recorders. In order to obtain as high a signal-to-noise ratio as practicable a machine has been obtained using tape 25 mm wide on which four tracks of 4 mm width are recorded; four tracks are needed to permit simultaneous stereo replay and recording. With certain modifications to the machine and the use of pre- and de-emphasis a weighted signal-to-noise ratio of 52 dB has been achieved for a single record/replay operation. This is the limiting factor in the overall signal-to-noise ratio for the system. Tape speeds of 93·7 mm and 750 mm/sec are used giving bandwidths of 13 kHz and 105 kHz respectively.

7. FIRST APPLICATION

A model of Maida Vale Studio 1 has been made using a scale ratio of 1 to 8, a photograph of which is shown in Fig. 1. Experiments are in progress using a model reverberation room to determine, from absorption measurements, the various substitutes for the absorbing materials used in the full-size studio. Reverberation and impulse measurements are being made in the model and compared with those of the original. A stereophonic tape of non-reverberant music has been recorded and reproduced through the system and the resulting sound quality compared with that from the same tape reproduced through two loudspeakers in the real studio.

The prime purpose of the first experiment is to validate the use of scale models both from the objective and subjective aspects. This involves developing the instrumentation (loudspeakers, etc.) to the extent necessary for satisfactory measurements and assessments.

8. CONCLUSIONS

The use of the acoustic modelling technique offers promise in allowing forecasting of the acoustical quality of proposed designs for studios, concert-halls, etc., in a convenient and economical way.

Experiments have commenced with a model of Maida Vale Studio 1 which will allow the technique to be evaluated and the necessary instrumentation developed.

9. REFERENCES

1. DAVIS, A.H. *and* FLEMING, N. Sound pulse photography as applied to the study of architectural acoustics. *J. Scient. Instrum.*, 1926, **III**, 12, p. 393.
2. DAVIS, A.H. 1926. The analogy between ripples and acoustic wave phenomena. *Proc. phys. Soc.*, 1926, **38**, 3, p. 239.
3. SPANDÖCK, F. 1934. Akustische modellversuche. *Annln. Phys.*, 1934, **20**, 4, pp. 345-360.
4. JORDAN, V.L. 1964. Acoustical considerations concerning New York State Theatre. *J. Audio Engng. Soc.*, 1965, **13**, 2, pp. 98-103.
5. SPANDÖCK, F. 1965. Die Vorausbestimmung der Akustik eines Raumes mit hilfe von Modellversuchen. 5th I.C.A., 1965, II, pp. 313-339.
6. BURD, A.N., GILFORD, C.L.S. *and* SPRING, N.F., 1966. Data for the acoustic design of studios. *B.B.C. Engng. Monogr.*, 1966, No. 64, November.
7. OBERST, H. *and* FRANKENFELD, K. 1952. Uber die Dämpfung der Biegeschwingungen dünner Bleche durch fest haftende Beläge. *Akust. Beik.*, 1952, 4, pp. 181-194.
8. GRIESE, H.J. 1964. Circuits of transistorized r.f. condenser microphones. *J. Audio Engng. Soc.*, 1965, **13**, 1, pp. 17-22.
9. KUHL, W. 1969. Summary of discussions. Use of acoustical scale-models for the study of studios and concert halls. EBU Report Tech 3089-E, 1969, October, p.46.
10. Non-reverberant music for acoustic studies. BBC Research Department Report No. 1969/17.

SMW

Printed by BBC Research Department, Kingswood Warren, Tadworth, Surrey